EXTREME DEEP SPACE COMMUNICATIONS

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Abstract

Recent work in deep space telecommunication systems has been performed in support of NASA's Mission to the Solar System planning activity. The results show that high bandwidth communications (greater than 1 Mbps) are feasible with communication infrastructure investments at targets of high exploration activity. These targets include Mars, Jupiter, and Neptune. Infrastructure improvements must also be made at the Earth. Key enabling technologies include Ka-band (32 GHz) communications, optical communication, large deployable apertures (sometimes coupled with power collectors,) advanced error-correcting coding, and compression. Commercial networking technology can be incorporated to provide a distributed communications and computing system across the solar system. This work indicates solutions to extreme deep space (beyond 40 AU) communications and operations problems. Communications capabilities between 10 and 100 Kbps should be achievable from 1,000 AU within 25 years. The technologies, infrastructure enhancements, and resulting performance capabilities are discussed in this paper.

Introduction

There has been much interest lately in the development of a long range plan for telecommunications within our solar system. Part of the interest stems from a NASA Office of Space Sciences (OSS) planning activity to develop a *roadmap* for the *Mission to the Solar System*. The Jet Propulsion Laboratory (JPL) has been leading this effort for NASA. The roadmap has been synthesized over the past six months with participation from a cross section of the American science community as well as technologists from JPL and various American companies. The roadmap covers robotic exploration for the period of time from now until the year 20?().

NASA realizes that solar system exploration will be an international activity. Foreign space agency plans have been factored into the roadmap activity. There will likely be an international planning activity that will follow NASA's acceptance of the roadmap recommendations.

In addition to developing a set of recommendations to NASA for missions to answer specific scientific questions, the roadmap team examined several of the key enabling technologies. One of these is telecommunications. The focus of the roadmap activity was on space missions within the solar system. However, the work that was performed in the telecommunications area can be extended to far outer planet and interstellar missions as well.

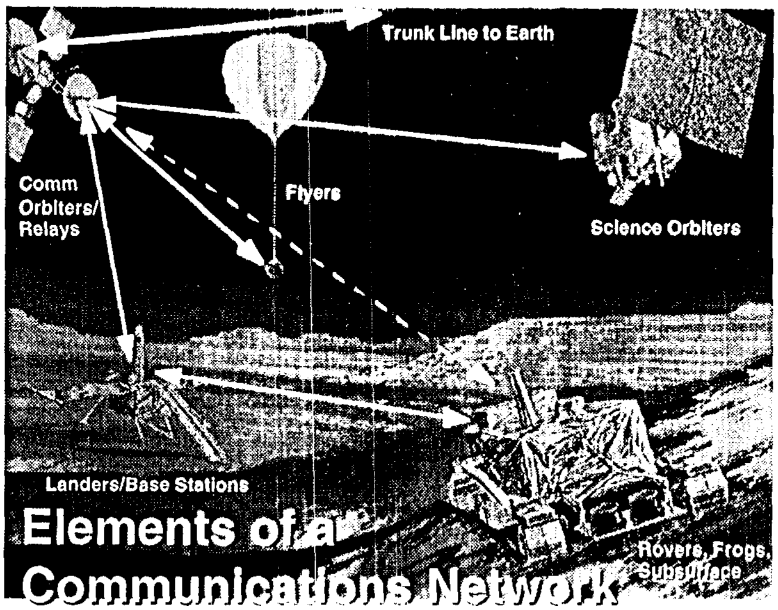

Figure 1.
The Mission to the Solar System roadmap team's vision for communications showing the trunk line as the principle communications channel between Earth and target bodies.

The Mission to the Solar System roadmap considered many aspects of the telecommunications challenge. The team considered the networking aspects of operating many spacecraft (and landers, rovers, ...) on a single target body using communications relay satellites. The team also examined the challenge of providing a low cost, low mass, high performance communications capability between the surface elements and a relay satellite. The team spent most of its energy predicting the performance, as a function of time, for the *trunk lines* - the main communications channels between Earth and the target bodies that will be explored. The trunk lines represent the hardest problem to solve for outer planet missions and beyond. This paper deals only with performance estimates and technology developments for the trunk lines.

The roadmap analysis included an examination of the key technologies required for the trunk lines and their probable availability over the next 25 years. Analyses were performed for three target body communications orbiters: Mars (2 AU), Jupiter (4 AU), and Neptune (30 AU.) The results showed that in the time frame of the roadmap, we could expect communication bandwidths of more than 1 Mbps at each of these targets - with much greater capabilities at Mars. Such large bandwidths were considered essential to provide a telepresence for the public during the exploration and to lay the infrastructure for subsequent piloted missions.

This work have now been extend to cover communications capabilities at 100 AU and 1,000 AU in the same period of time. The results indicate that it will be possible to support data rates of about 10 to 100 Kbps from missions at 1,000 AU within 25 years.

Technology Predictions

In order to estimate communications link performance over the next 25 years, one must predict the evolution of critical communications technologies. This is an imperfect exercise. It is also, at the moment, not cost constrained.

The technologies listed below are not meant to represent all relevant technologies – only those that are seen as enabling for the main communications links. Analyses were performed for both radio frequency (RF) Systems and optical systems.

RF Technologies

Ka-Band

NASA's Deep Space Network (DSN) is already developing the capability to communicate with deep space missions at 32 GHz (Ka-band.) Although the inherent advantage over the DSN's current standard frequency (8.4 GHz, or X-band) is just under 12 dB, Earth atmospheric effects, pointing depredations, and system noise performance limits the current advantage to about 4 dB.

NASA's DSN Technology Development Program is working to increase the relative advantage of Ka-band over X-band. The advantage (over current X-Band performance) is expected to be about 6 dB by the year 2020.

Currently, only the DSN's 34m beam waveguide [1] antennas can support Ka-band systems. In this study it is assumed that the DSN's larger 70m antennas will be equipped with Ka-band receive capability by 2010.

Power

Throughout the 25 year time period, a steady increase in the availability of on-board spacecraft solar power is assumed. This gain will come from increased efficiency in the solar cells, larger deployable arrays, and solar collector technology (including the *power antenna* [2].)

For Mars missions, the available power for communications could go as high as 300 Watts. For Neptune and beyond, this decreases to about 75 Watts, and will probably require the use of radioisotropic thermal generators (RTGs.)

Spacecraft Transmitter Efficiency

A steady increase in the efficiency of spacecraft transmitters during the 25 year time period is assumed. Current efficiencies are of the order of 50% for X-Band and 30% for Ka-Band. By the end of the 25 years, these are likely to improve to 65% and 50% respectively.

Spacecraft RF Antennas

The performance with both fixed type parabolic antennas and large inflatable reflectors [3] were calculated for this analysis. Other technologies that will probably fall in between these extremes include phased array and reflect array [4] antennas.

For inflatable technology, it was assumed that, by 2020, 25m antennas with good Ka-Band performance at Mars and Jupiter could be flown, with somewhat smaller sizes (due to mass constraints) at Neptune and beyond.

RF Modulation Scheme

Currently, all deep space missions use bi phase shift keying (BPSK) modulation. The new Block V receivers in the DSN are capable of supporting quad phase shift keying (QPSK) modulation. Other, more bandwidth efficient modulation schemes could, conceivably, be used in deep space during the next 25 years. It was assumed that in 25 years, deep space links would be capable of 64 quadrature amplitude modulation (QAM) [5] modulation with appropriate trellis coding.

Error Correcting Coding

Recent advances in error correcting coding has resulted in the discovery of codes that achieve performance within 1 dB of Shannon's theoretical limit for the deep space channel [6]. These *turbo codes* were assumed for all missions by the end of the 25 year time frame. Figure 2 shows the performance of one of the new turbo codes in relation to some other codes that are used in NASA deep space missions. Systems that allow the coding and decoding of the turbo codes at high data rates (at least 1 Mbps) will be required.

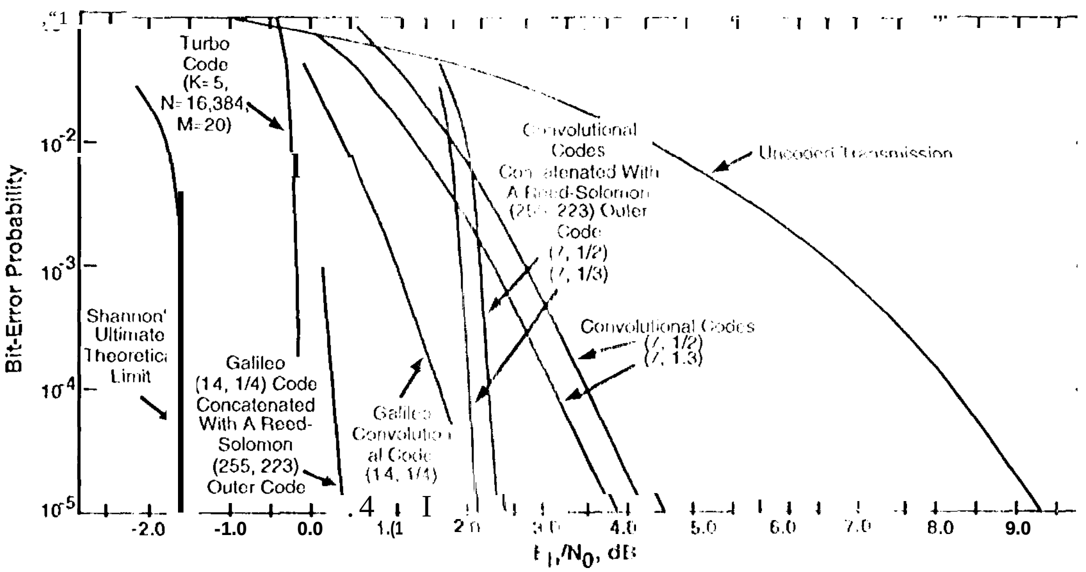

Figure 2.
Relative performance of various error correcting codes including a new turbo code

Receiver Noise Performance

Currently, the DSN's equivalent receiving noise temperature (T_{sys}) is about 30 K at X-band and 40 K and Ka-band. It is assumed that this will improve to 20 K and 30 K respectively in 25 years. The important technological developments include better solid state detectors (HEMTs [7]) as well as cryogenic cooling of substantial portions of the detector systems

Pointing

In order to achieve the gains resulting from higher carrier frequencies and larger transmit and receive apertures, both the spacecraft and ground stations must improve their pointing accuracy. It was assumed that pointing technology will advance at a rate that keeps the losses from pointing errors constant over the next 25 years.

Optical Technologies

Optical Communications Wavelength

Current optical communications work is concentrated at a wavelength of 1.064 μm. By the year 2005, it is expected the technology for communication at 0.532 μm will be available for flight. This will allow an incremental jump in performance.

Spacecraft lasers

The efficiency of solid state flyable lasers is assumed to increase for its current value of about 10% to better than 30% over the next 25 years. At the same time, the radiated power is predicted to increase from 3 W to 20 W.

Low mass and cost space terminals

JPL has been working on the challenge of creating a low mass and low cost communications terminal for deep space missions using optical communications technologies. Although none of these terminals have flown in space yet, several prototypes, including the Optical Communications Demonstrator [8]) have been tested in the laboratory. These terminals would have an optical aperture of 0.1 m.

Figure 3 shows a possible configuration for a deep space optical terminal. It would have a mass of about 3.5 kg and radiate 15 W of power. Such a terminal could be available for flight as early as next year.

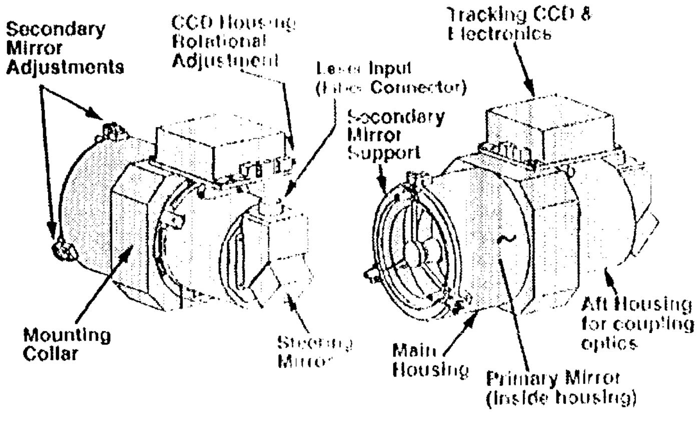

Figure 3.
Deep space optical flight terminal

More advanced versions, that integrate the optical communications instrument with a science imaging system, could be ready for flight by 2000. These would have a mass of about 10 kg and radiate approximately 35 W of power.

Earth Receive Apertures

There is currently no operational capability for deep space optical communications. Demonstrations have been performed using modified astronomical observatories [9, 10],

By the year 2000, there could be a limited ground-based optical communications capability to **support** demonstrations in deep space [11]. This stations could have a 10m non-diffraction limited receive aperture. This would be more than enough to support hundreds of kilobits of communications from Saturn-like distances

In order to make this capability truly operational, several copies of the 10m terminal would be built to achieve both continuous coverage with deep space targets and spatial diversity to combat the effects of Earth's weather. At least three, and maybe as many as five such stations would be needed to support operational deep space missions [12]. These could be in place by 2005.

By 2010, the Earth receive capability could be increased either by building larger ground-based apertures, or by placing the terminals in Earth orbit [13, 14].

Receive Filters

Current state-of-the-art for receive system detection filter bandwidth is about 10 Å. Over the next 25 years, this should decrease to better than 1 Å through the use of technologies such as the Faraday Anomalous Dispersion Optical Filter [15].

Detectors

Currently, all optical communications demonstrations with deep space have utilized avalanche photodiodes (APDs) to measure incoming photons. By the year 2015, solid state photomultiplier tube.s (SS-PMTs) will be available.

Pointing

Just as in the RF case, the pointing of both the spacecraft and Earth terminal apertures is critical to the performance of the link for optical communications.

The first deep space missions to optical communications will likely have a cooperative pointing system. In this case, a beacon signal will be sent from the Earth station. After acquisition, the two terminals would track each other's signal to achieve a closed loop pointing.

By 2000, a spacecraft system that finds the optical image of the Earth could allow sufficient pointing accuracy to eliminate the need for an Earth terminal beacon for signal acquisition. More sophisticated systems that use star trackers and other on-board sensors could allow even better open loop pointing by 2005.

By 2010, such on-board autonomous pointing systems could be further improved by using a non-mechanical fine steering technique for the spacecraft terminal.

The Analysis for Mission to the Solar System

Using the technology projections above, link performance estimates were developed for three target body orbiters: a Mars orbiter, a Jupiter orbiter, and a Neptune orbiter. It was assumed that the largest launch vehicle available for this exercise is a Delta II. The analysis was performed in five year intervals beginning in 1995 (present capability) and ending in 2020.

For each year, six link performances were calculated: aggressive and conservative estimates for X-band, Ka-band, and optical systems. The results are shown in Figure 3. The areas in the graphs are bounded by the best aggressive case on the top and the best conservative case on the bottom. All three graphs eventually use optical communications to bound the areas as time progresses.

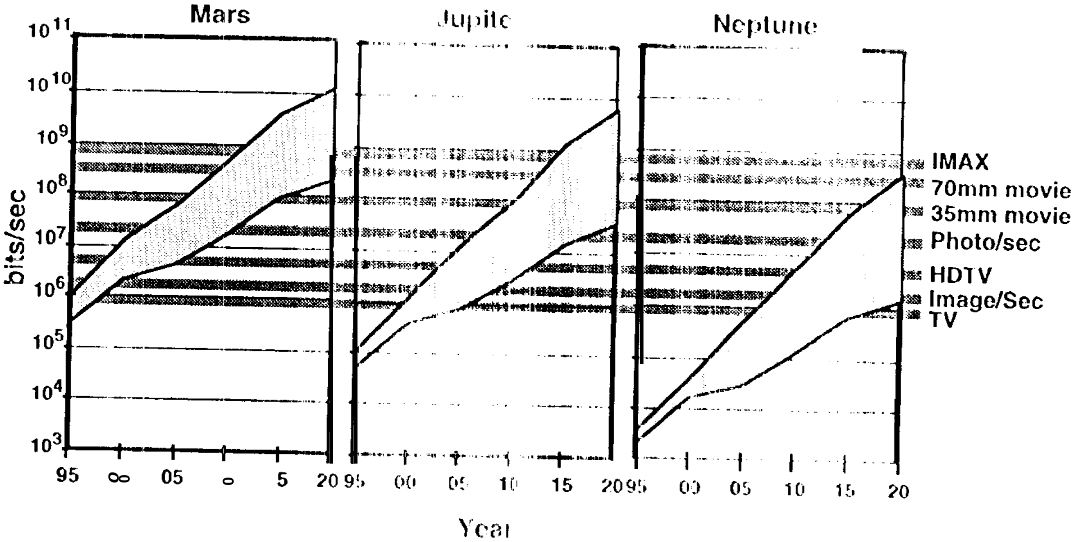

Figure 3.
Mission to the Solar System capabilities projections for communications orbiters

The horizontal lines through the graphs represent the capability that would be required to support real time communication of various common data types. These range from broadcast quality television (USA NTSC) to IMAX high resolution motion pictures. Aggressive compression technology was assumed for all of these data types.

The Neptune communications orbiter was, by far, the most challenging. It requires a Delta III launch vehicle and an RTG to supply sufficient power for the link. Optical communications provides the only option for 1 Mbps communications bandwidth in this time frame.

The basic conclusion for the Mission to the Solar System roadmap exercise is that a capability at least as good as commercial broadcast television could allow the public to participate in exploration of the entire solar system - if there is enough investment in both flight and ground infrastructure.

Extending the Analysis for Far Deep Space Missions

All the same assumptions about the availability of key technologies remain valid in the calculations for far outer solar system link performance. In addition, since there is no target to orbit for these missions, the spacecraft mass that had been devoted to orbit capture and maintenance for the above three cases can be applied to the communication system. This extra could go toward generating more power, providing twice as much power from RTGs (150 W) beginning in 2010. This makes the link performance estimates look better in comparison to the Mars, Jupiter, and Neptune cases than one might expect from the inverse square distance loss.

An additional technology that was considered for both the 100 AU and 1,000 AU missions was arraying of ground antennas. Allowing for a 0.3 dB combining loss by 2020, an array consisting of a 70m and four 34m antennas (the planned configuration of all three DSN complexes by 2020) would have the performance slightly better than a single 94m antenna. Since continuous coverage is not likely to be a requirement for such missions, such large amounts of ground resources can be applied for short periods of time

The results of the aggressive analysis are shown in tabular form in Table 1, together with the assumptions on available technologies. The conservative case differs from Table 1 in two main ways: the RF antennas are assumed to be fixed, 1.5m dishes, and the optical technology items are assumed to mature ten years later. In [16] and [17], similar calculations are performed to estimate the communications performance of a 1,000 AU mission for X-band and optical systems. The results are comparable to those presented here for the 2010-2015 time when one accounts for the differences in assumptions.

	Technology Area	1995	2000	2005	2010	2015	2020
ommon	Spacecraft System Power	75	75	75	150	150	150
-band	Transmitter Efficiency	50%	53%	56%	59%	62%	65%
	RF Transmit Power (W)	?0	32	33	70	74	78
	Spacecraft Antenna Diameter (m)	3	6	6	10	10	15
	Ground Antenna Diameter (m)	0	70	82	82	88	94
	Tsys (K)	?0	20	20	20	20	20
	Ground Aperture Efficiency	65%	65%	65%	65%	65%	65%
	Modulation Scheme	BPSK, 1/4TC	BPSK, 1/4TC	BPSK, 1/4TC	BPSK, 1/4TC	BPSK, 1/4TC	BPSK, 1/4TC
	Coding	Turbo	Turbo	Turbo	Turbo	Turbo	Turbo
	Data Rate @ 100 AU (bps)	7.63E+02	7.32E+03	1.04E+04	6.11E+04	7.50E+04	2.03E+05
	Data Rate @ 1000 AU (bps)	7.63E+00	7.32E+01	1.04E+02	6.11E+02	7.50E+02	2.03E+03
a-band	Transmitter Efficiency	30%	34%	38%	42%	46%	50%
	RF Transmit Power (W)	10	15	20	44	48	51.5
	Spacecraft Antenna Diameter (m)	1.5	3	6	6	10	15
	Ground Antenna Diameter (m)	70	70	82	82	88.4	94.3
	Tsys (k)	40	30	30	30	30	30
	Ground Aperture Efficiency	50%	50%	62%	50%	50%	50%
	Modulation Scheme	BPSK, 1/4TC	BPSK, 1/4TC	BPSK, 1/4TC	BPSK, 1/4TC	BPSK, 1/4TC	BPSK, 1/4TC
	Coding	Turbo	Turbo	Turbo	Turbo	Turbo	Turbo
	Data Rate @ 100 AU (bps)	7.13E+02	5.70E+03	4.18E+04	1.04E+05	3.64E+05	1.02E+06
	Data Rate @ 1000 AU (bps)	7.13E+00	5.70E+01	4.18E+02	9.19E+02	3.23E+03	8.89E+03
ptical	Transmitter Efficiency	? 0	75'L.	70%	75%	75%	75%
	Wavelength (A)	1.064	1.064	0.532	0.532	0.532	0.532
	Laser Power (W)		5	5	10	20	20
	Spacecraft Telescope (m)	0.3	0.3	0.5	0.5	1	1
	Receiver Location	ground	[illegible]	ground	Earth orbit	Earth orbit	Earth orbit
	Filter Bandwidth (A)	10	.	1	1	1 1	1
	Detector Type	APD	APD	APD	APD	SS-PMT	SS-PMT
	Ground Receiver Efficiency	56%	56%	56%	56%	56%	56%
	Data Rate @ 100 AU (bps)	1.00E+02	1.00E+03	4.00E+04	4.00E+05	9.00E+06	7.00E+07
	Data Rate @ 1000 AU (bps)	1.00E+00	1.00E+01	4.00E+02	4.00E+03	9.00E+04	7.00E+05

Table 2.
Aggressive 100 AU and 1,000 AU capabilities projections for communications orbiters for X-band, Ka-band and optical systems

Figure 4 shows these results graphically in the same form as in the previous section. The areas in the graphs are bounded by the best of the aggressive and conservative results for each year.

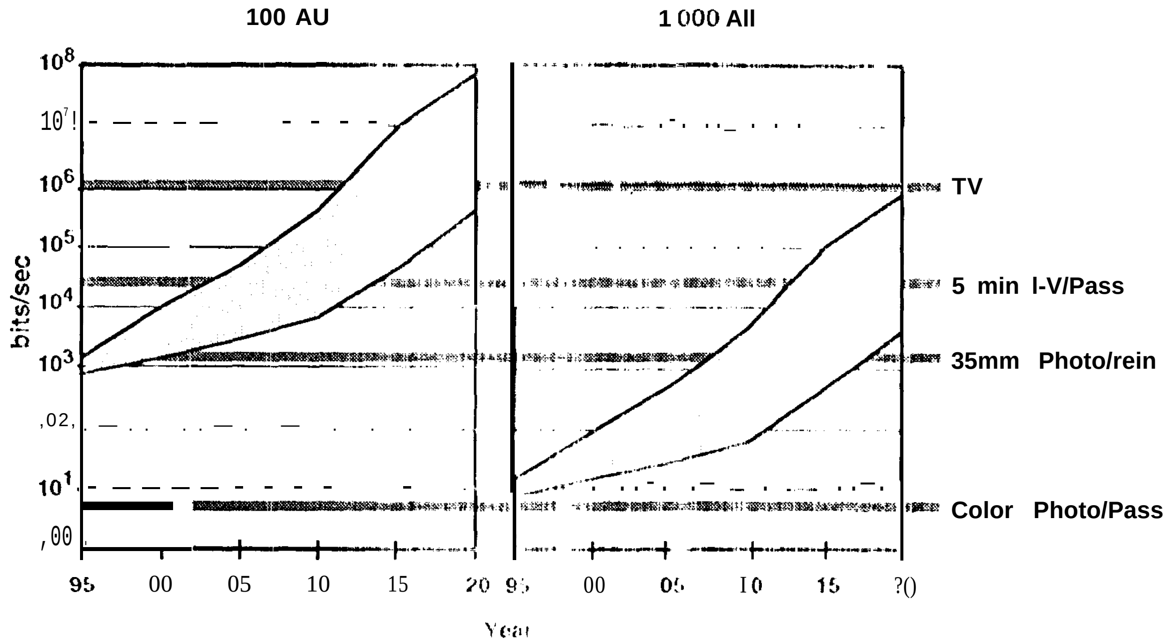

Figure 4.
Capabilities projections for communications from missions at 100 AU and 1,000 AU

Conclusions

The calculations performed here indicate that, even in the near term, communications capabilities from far outer solar system missions (up to 1,000 AU) are sufficient to support meaningful science and even public involvement. With today's technology, missions with kilobit data rates can be supported at 100 AU. Within 20 years, this capability will exist for missions at 1,000 AU. With an aggressive program of communications technology and infrastructure development, even greater capabilities will be possible -- up to supporting real time broadcast quality television from 100 AU and many minutes of television-quality video each day from 1,000 AU.

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